NASA TECHNICAL MEMORANDUM

NASA TM X-2680

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ANALYSIS OF A BORON-CARBIDE-DRUM-CONTROLLED CRITICAL REACTOR EXPERIMENT

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • NOVEMBER 1972

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM X-2680		

4. Title and Subtitle	5. Report Date
ANALYSIS OF A BORON-CARBIDE-DRUM-CONTROLLED CRITICAL REACTOR EXPERIMENT	November 1972
	6. Performing Organization Code

7. Author(s)	8. Performing Organization Report No.
Wendell Mayo	E-7071
	10. Work Unit No.
9. Performing Organization Name and Address	503-25
Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135	11. Contract or Grant No.
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	Technical Memorandum
National Aeronautics and Space Administration Washington, D.C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

In order to validate methods and cross sections used in the neutronic design of compact fast-spectrum reactors for generating electric power in space, an analysis of a boron-carbide-drum-controlled critical reactor was made. For this reactor the transport analysis gave generally satisfactory results. The calculated multiplication factor for the most detailed calculation was only 0.7-percent Δk too high. Calculated reactivity worth of the control drums was \$11.61 compared to measurements of \$11.58 by the inverse kinetics methods and \$11.98 by the inverse counting method. Calculated radial and axial power distributions were in good agreement with experiment.

17. Key Words (Suggested by Author(s))		18. Distribution Statement
Nuclear reactors	Spacepower reactor	Unclassified - unlimited
Critical experiment	Boron control	
Neutronic analysis		

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	26	\$3.00

* For sale by the National Technical Information Service, Springfield, Virginia 22151

ANALYSIS OF A BORON-CARBIDE-DRUM-CONTROLLED CRITICAL REACTOR EXPERIMENT

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SUMMARY

Fast-spectrum nuclear reactors as heat sources for the generation of electric power in space are part of the technology program at the Lewis Research Center. A neutron absorber, such as boron carbide enriched in boron-10, incorporated in control drums is one type of reactivity control method that is being considered. In order to validate methods and cross sections used in the neutronic design of these reactor concepts, critical experiments were performed at Atomics International to check design calculations. The experiments incorporated materials for high-temperature, long-life reactors such as uranium-235 nitride fuel, lithium-7 coolant, and refractory-metal structure and reflectors. The critical assembly diameter is close to the diameter considered for the power reactor concepts. The fuel-pin-in-honeycomb-lattice core design and molybdenum radial and axial reflectors were also simulated in the critical experiments. The reactor was controlled by rotating control drums containing boron carbide.

The multigroup two-dimensional transport analysis gave generally satisfactory results. The calculated multiplication factor for the most detailed spatial calculation was only 0.7-percent Δk too high. The calculated reactivity worth of the control drums was \$11.61 compared to \$11.58 measured by the inverse kinetics method and \$11.98 measured by the inverse counting method. Calculated radial and axial power distributions were in good agreement with experiment.

INTRODUCTION

Fast-spectrum reactor concepts that use various reactivity control methods have been considered in the technology program at the Lewis Research Center. The nuclear reactors would serve as heat sources for systems generating electric power in space. Reversible hydriding of yttrium zones (ref. 1), axially translating radial reflectors

(ref. 2), rotating poisoned control drums (ref. 3), and rotating fueled control drums (refs. 4 and 5) are examples of control methods previously considered. Performance goals established were generally for about 2.2 thermal megawatts for 50 000 hours with a lithium-7 coolant outlet temperature of 1222 K.

The conclusions in reference 3 indicate that reactivity control using boron-10 carbide control drums located outside the pressure vessel might be marginal. Since that report was written (1969), several other design concepts using boron-10 carbide for control have been examined. These include the use of in-core control rods, the use of control rods in conjunction with control drums, and the use of control drums located in dry wells inside the pressure vessel. In each case, the major consideration was to provide adequate reactivity control for the long-life (50 000 hr), 2.2-thermal megawatt reactor requirements.

More recently, as part of an experimental program (ref. 6) under contract NAS 3-12982 and an extension of that program (ref. 7) under contract NAS 3-14421, a critical assembly using boron carbide control drums was built and operated by Atomics International. Preliminary calculations of these experiments indicated an underestimation of the measured control-drum worth. With this discrepancy in mind, a reexamination of the methods and cross sections used in the calculation of the critical assembly and in the previous design concept calculations of boron-carbide-controlled reactors (such as in ref. 3) is in order.

Although a comprehensive series of experiments were performed at Atomics International, the present work is limited to those associated with the boron-carbide-drum-controlled reactor. This report presents an analysis of the reactor critical experiments to determine possible sources of the discrepancy in control-drum reactivity calculations mentioned previously.

DESCRIPTION OF EXPERIMENTS

Complete details of the critical assembly design and experiments are given in references 6 and 7 so that only a brief description pertinent to this report is given here.

Figure 1 shows the fuel element used in the critical assembly. The fuel element has molybdenum end reflectors. The reflector piece and the ceramic-like lithium-7 nitride are eccentrically sealed between the honeycomb tube and the fuel tube. The cylindrical molybdenum reflector piece can be taken out of the fuel tube after removal of the jackscrew - neoprene-seal assembly, thus providing access to the fuel region for fuel loading adjustments. Uranium metal rods (93.145-percent ^{235}U) are used for the fuel. Three sizes are used so that relatively fine adjustments can be made to assure fuel loading uniformity between fuel elements. The fuel rod bundle is centered inside the fuel tube by tantalum centering rings at each end of the fuel bundle. The 0.051-centimeter offset

between the fuel tube and the honeycomb tube is for the purpose of measuring radial compression-expansion effects resulting from fuel displacement, as would occur with temperature changes in the design core. The normal (null) position is such that the mark on the end cap (see fig. 1) is perpendicular to the radius vector to the centerline of the core.

The fuel elements are positioned in a lattice (with a pitch of 2.215 cm), as shown in figure 2, by grid plates with holes into which the fuel-element end fittings are inserted. The lattice forms a six-pointed star shape composed of 181 fuel elements. Between the star-points are located the control drums. As shown in figure 2 the boron carbide is inside aluminum cannisters bolted to the massive molybdenum drum center piece. Opposite the boron carbide is another aluminum cannister filled with molybdenum plates. The stationary and movable radial reflector pieces are also of molybdenum. The design is such that four of the six radial reflector pieces can fall away from the core for scramming the reactor. The tantalum (simulating a pressure vessel) attached to the radial reflector pieces is therefore also segmented.

Measurements included the critical loading (or excess reactivity near critical), the radial and axial power distributions, and the worth of single control drums and of all six control drums. Details of the measurements and procedures used are fully described in references 6 and 7.

ANALYSIS PROCEDURE

In this section the geometric models and procedures used in the analysis of the experiments are described. Sufficient detail is provided so that the same calculations can be repeated, using updated cross sections as they become available, if desired.

Three separate energy-group structures are used, as shown in table I. Previous calculations have been done primarily with the four-energy-group cross sections, with occasional checks made by using the 13-group set. Generally, the four-group set has been found adequate for preliminary calculations and for surveys. A 26-group set was employed for the critical experiment analysis to check the adequacy of the fewer-group treatment.

Two sets of cross sections were used. One set, designated GAM, is fairly old and was used in nearly all previous calculations during the past few years. The second set, labeled GAM(ENDF), incorporates a number of isotopes from the ENDF/B cross-section library as processed by the SUPERTOG program (ref. 8) for use with the GAM-II program (ref. 9). This program was used for spectrum averaging all cross sections used in this study. Table II lists the ENDF/B material numbers used in GAM-II. With the GAM(ENDF) set, the older GAM isotopes were used to supplement the list in table II as required.

Figure 3(a) shows one of the 1/4-core calculation models used in the XY calculations. The XY grid was superimposed over the experimental geometry shown in figure 2 in such a manner as to represent the important regions. A certain amount of homogenizing is done to reduce mesh interval requirements. Briefly, the calculation model geometry is as follows:

(1) The fuel region is based on cells. The materials are smeared within the cell.

(2) The aluminum cans around the boron carbide powder and the molybdenum plates are smeared into the reflector region, which includes all materials inside the pressure vessel except the boron carbide regions and the fuel regions.

(3) In order to conserve mesh intervals, the exact area of the pressure vessel is not preserved; however, the atom density of the tantalum is adjusted accordingly to preserve the correct number of atoms.

(4) For one set of calculations, which incorporate a void explicitly between the control drums and the core fuel cells, the reflector materials and area are adjusted somewhat, though the total number of atoms of the reflector materials is preserved (fig. 3(b)).

The input axial and radial mesh specifications and the material numbers by region as used in the XY spatial calculations are listed in the appendix just as used in the DOT-IIW programs (ref. 10). Also listed are the atom densities for each region (table VII). The weights and dimensions of each piece of the critical assembly as described in references 6 and 7 were used in determining the atom densities and regions.

In order to account for the end reflector and axial effects in the calculations, an RZ model was also established. Figure 4 shows the RZ model used; and table III lists the volume percents of constituents in each region, along with consistent densities of the materials, so that the atom densities used in the calculations can be reproduced. In the radial direction, at Z = 0, the RZ model is consistent with the XY model from which it was derived.

Information obtained from the RZ calculations consists of axial power distributions and the effective height for use in determining transverse leakage "cross sections" for use in the XY calculations. The transverse leakage cross section, $\sum^{i}_{L_g}$ is defined as

$$\frac{\sum^{i}_{tr_g}\left(\frac{\pi}{\sqrt{3}}\right)^2}{\left(\sum^{i}_{tr_g} H_{eff} + 1.42\right)^2}$$

where $\sum^{i}_{tr_g}$ is the macroscopic transport cross section for group g and region i, and H_{eff} is an effective height (core length + reflector savings) determined by running one-

dimensional radial calculations (Z = 0) and varying the height until the same multiplication factor as given by the RZ calculation is obtained. For a given cross-section set and quadrature order, H_{eff} is assumed to be constant whether the poisoned portion of the control drums are rotated fully in or fully out. Previous calculations have indicated this is a good assumption. The XY calculations are used to obtain the radial power distributions, the effective multiplication factor, and the reactivity control worth of the drums.

COMPARISON OF EXPERIMENTS AND CALCULATIONS

The fuel loading in the critical assembly was 143.797 kilograms (corrected for the protective coating) of 93.145-percent enriched uranium. This fuel loading resulted in an excess reactivity of \$1.606 with the poisoned portion of the control drums rotated fully out. With an effective delayed neutron fraction of 0.0067, this excess reactivity corresponds to a multiplication factor k of 1.011; the calculations in this section are to be compared with this value.

Effect of Low-Order to High-Order Calculations

Table IV lists calculations made to determine the effect of varying the number of energy groups, the quadrature order, and the order of the Legendre expansion of the scattering cross sections. GAM cross sections were used, and both the RZ geometry and XY geometry results are tabulated for the "poison-out" case. The XY geometry corresponds to the second set in the appendix with 36X by 34Y intervals. The trend in multiplication factor generally follows that observed previously (refs. 5, 11, and 12) in that the higher order calculations give lower multiplication factors. Little benefit is observed in going beyond the 13-group S_4P_1 treatment. The results have been rounded to the third decimal, corresponding to about ±0.05-percent-$\Delta k/k$ (±7.5 cents) accuracy. Because of slight variations in the calculated effective height, the XY results show less change between low-order and high-order calculations. The XY results are the ones to compare with the experimental multiplication factor of 1.011 since the XY calculations incorporate the axial effects (through the effective height) and account for the azimuthal asymmetry more accurately than the RZ model can. Thus the higher order calculations give a multiplication factor 1.2-percent Δk too large when this geometric model is used. Another XY model, which more closely matches the experiment in that an explicit void region appears between the control drums and the core, was also used (fig. 3(b), geometry 4 in the appendix). This more-detailed model gave better agreement; k was only 0.7-percent Δk too large.

Effect of Using GAM and GAM(ENDF) Cross Sections

The calculations were made in the manner described in the preceding section, except that GAM(ENDF) cross sections (table II) were substituted for the GAM set. The GAM-(ENDF) set gave a multiplication factor 0.9-percent Δk larger than the GAM set for the 13-group S_4P_1 calculation procedure. The 26-group set showed a similar tendency to calculate larger multiplication factors. Since uranium-235 is an important and major constituent in the critical experiments, an independent comparison was made between the GAM and GAM(ENDF) cross sections for the fuel.

Reference 13 describes a GODIVA-like spherical critical experimental performed at the Oak Ridge National Laboratory. Calculation of the experiment using GAM cross sections (S_8P_1, 26 group) gave a multiplication factor 0.6-percent Δk larger than the experimental value. (This is fairly consistent with the 0.7-percent Δk overestimate discussed in the preceding section.) Use of the GAM(ENDF) cross sections (material 1044 for ^{235}U) indicated a multiplication factor 0.8-percent Δk larger than when the GAM set was used, which is again consistent with the results for the boron-carbide-drum-controlled experiment. Thus, we are led to suspect the GAM(ENDF) cross sections for uranium-235 (material 1044). The ENDF/B uranium cross sections have been updated but are not available as yet for use with the GAM program. It should be pointed out that, as in most calculations of the complexity of those in this study, off-setting discrepancies in cross sections can lead to good agreement with experimental results. In this study, the boron-10 cross sections in GAM are clearly in error (discussed in the next section); the GAM(ENDF) set may also be wrong but to a lesser extent. Similarly, we can infer probable errors in the uranium-235 cross sections based on the calculation of these two critical experiments. However, an element-by-element substitution for the other materials was not done, which precludes any judgement as to their accuracy.

Drum Control Worth

The reactivity worth of the control drum was measured in two different ways. One measurement used was the inverse kinetics method to measure the worth of each control drum. The average worth per drum was \$1.93. Assuming no adjacent drum interactions, the worth of six drums would be \$11.58. The inverse counting method was also used to measure the worth of all six drums ganged. This method is not considered highly accurate but gave a reactivity worth of \$11.98, which is in fair agreement with the inverse kinetics measurement. Both methods are explained in detail in references 6 and 7.

Initial calculations for the reactivity worth of the control drums were too low for two reasons:

(1) The old GAM cross sections for boron 10 had too little absorption in the energy range of importance - between about 100 keV and 2 MeV. This was suspected (ref. 14) and the ENDF/B cross-section library (material 1009) reflects significantly larger absorption cross sections. Table V shows the GAM and GAM(ENDF) cross sections for the 26-energy-group structure.

(2) Initial calculations were done with reflector material smeared in between the control drums and the active core (XY geometries 1 and 2 in the appendix). This reflector material effectively shields the control drum and reduces control swing. The XY geometries 3 and 4 in the appendix incorporate an explicit void region between the drums and the core which more closely matches the experimental geometry. Table VI gives results of the various calculations. The control swing is not very sensitive to the order of the calculations; compare cases 1, 2, and 3 and compare cases 5 and 7. Also note that the use of the boron-10 cross sections from ENDF/B (cases 4, 5, and 7) have control swings about \$1 larger than those calculated by using the older GAM cross sections for boron-10 (cases 1 to 3). Case 6 is special in that it was performed by using the XY geometry setup to show the explicit void region between control drums and core. The reactivity worth of \$11.61 is in good agreement with the experimental values.

Axial Power Distributions

The relative axial power distribution calculated with the RZ model is shown in figure 5, along with the experimental points (ref. 7). The measurements were made by gamma-scanning small-diameter fuel wires. The experimental points at three radial positions were averaged to obtain a single value at each axial location. Several experimental values (about 4 percent of the total measured points) that showed unexplained irregularities were discarded in the averaging process. Also, since the RZ calculation assumes symmetry at the axial midplane, the corresponding experimental points above and below the midplane were averaged to obtain the values plotted in figure 5. An inspection of the data in reference 7 indicates that the separability of radial and axial flux solutions is a good assumption and that axial asymmetry was not significant. Thus, calculation and experiment (fig. 5) are generally in good agreement.

Radial Power Distributions

Figure 6 shows a 30° sector of the critical assembly. The relative power density values for calculation and experiment are shown with the corresponding fuel elements and at two locations in the boron carbide region. Three axial points for each radial position

were measured and averaged to obtain the values shown in the figure. Again, a small number of unexplained irregular points were discarded in the averaging procedure. Agreement is fairly good for all points shown in figure 6. The 9 percent difference in the outer boron carbide region is the largest difference noted, but it is in a relatively unimportant region; the multiplication factor would not be sensitive to this discrepancy.

SUMMARY OF RESULTS

A boron-carbide-drum-controlled fast-spectrum critical assembly was analyzed to check calculation methods and cross sections used in nuclear reactor design. The critical assembly used enriched uranium fuel, tantalum structure, lithium and nitrogen in the form of lithium nitride, molybdenum reflectors, and boron carbide control drums; all these materials are being considered for possible use in space power reactor concepts.

It was found that S_4P_1 calculations using 13 energy groups were adequate for the analysis. Both GAM and GAM(ENDF) cross sections were used. In computing the multiplication factor the GAM set was 0.7-percent Δk high, while the GAM(ENDF) set was 1.6-percent Δk too large based on the most detailed two-dimensional geometric representation. An independent check of a small fast-spectrum critical reactor indicated that the larger error with the GAM(ENDF) cross sections was due to the GAM(ENDF) uranium-235 (material 1044).

In calculating the reactivity worth of the control drums, it was found that the newer boron-10 cross sections (ENDF material 1009) were preferable. When the GAM(ENDF) boron-10 cross sections were used, the calculated reactivity worth of the control drums was \$11.61 compared to \$11.58 measured by the inverse kinetics method and \$11.98 measured by the inverse counting method. With the older GAM boron-10 cross sections, an underestimate of about \$1 was observed.

The importance of a detailed geometric model was confirmed in the calculation of the control worth of the drums. Explicitly representing the void region between drums and core increased the control swing by about \$1 compared with a less-detailed model in which reflector material was smeared into that region.

Radial and axial power distributions were in good agreement with the measurements.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 5, 1972,
503-25.

APPENDIX - MATERIAL AND GEOMETRY SPECIFICATIONS FOR CALCULATIONS FOR B_4C-DRUM-CONTROLLED REACTOR EXPERIMENT

This appendix records the atom densities (table VII) for each material used in the XY calculations and provides card images of the geometric specifications as used by the DOT-IIW program for each of the four geometries. The geometries are referred to in the text by numerical order in which they appear in the appendix. Briefly, the designations are

(1) 37X by 35Y intervals, control-drum poison inserted, six materials (regions)

(2) 34X by 36Y intervals, control-drum poison rotated full out, six materials (regions)

(3) 37X by 35Y intervals, control-drum poison inserted, seven materials (regions), explicit void region between control drums and core

(4) 44X by 45Y intervals, control-drum poison rotated full out, seven materials (regions), explicit void region between control drums and core

The card images are as follows:

```
   37X BY 35Y GEOMETRY - MESH AND MATERIAL SPECIFICATIONS - POISON IN
 4*                    0.0
   1.08          2.08          3.3           4.20          4.85          5.40
   6.20          6.7           7.7           8.7           9.7           10.6894
   11.0          11.3          11.6712       12.5          13.41         14.20
   14.4          15.60         16.3          17.6          18.25         19.20
   19.80         20.1          21.62         23.00         23.7          24.80
   25.50         26.50         27.20         27.80         28.20         28.6
   29.291
 2*                    0.0
   1.08          2.215         3.3           3.45          4.4           4.80
   5.54          5.89          6.4           7.20          7.5           8.80
   9.50          10.51         12.2          13.25         13.8          14.3
   14.6          15.4          15.7          16.5          17.6          18.812
   19.1844       21.70         22.40         23.60         24.758        25.90
   26.90         27.60         28.20         28.6          29.291
 8$
26R          110R          2             5
23R          113R          2             5
21R          115R          2             5
19R          117R          2             5
19R          1             2  5R         311R          2             5
16R          1  3R         2  5R         312R          2             5
16R          1             2  7R         312R          2             5
12R          1  5R         2  7R         312R          2             5
12R          1  4R         2  7R         311R          2  3R         5
12R          1  3R         2  8R         311R          2             5  2R         6
12R          1  3R         2  7R         312R          2             5  2R         6
12R          1  2R         2  8R         312R          2             5  2R         6
12R          1             2  8R         311R          2  3R         5  2R         6
12R          1             2  8R         311R          2             5  4R         6
12R          1             2  7R         312R          2             5  4R         6
```

```
          211R        1 2R        2 5R        313R        2           5
 4R       6
 3R       2 9R        1 3R        2 3R        312R        2 3R        5
 4R       6
 2R       4           2 9R        1 3R        2 3R        312R        2
          5 6R        6
 3R       4 2R        2 7R        1 4R        2           313R        2
          5 6R        6
 4R       4           2 7R        1 4R        2           313R        2
          5 6R        6
 5R       4 3R        2 4R        118R        2           5 6R        6
 6R       4 2R        2 4R        116R        2 3R        5 6R        6
 7R       4 3R        2 2R        116R        2           5 8R        6
 8R       420R        2           5 8R        6
 8R       417R        2 4R        5 8R        6
25R       2           511R        6
22R       2 4R        511R        6
22R       2           514R        6
17R       2 6R        514R        6
17R       2           519R        6
13R       2 5R        519R        6
13R       2 2R        522R        6
 7R       2 8R        522R        6
 7R       2           529R        6
 8R       529R        6
```

34X BY 36Y GEOMETRY - MESH AND MATERIAL SPECIFICATIONS - POISON OUT

```
 4*                    0.0
   1.08       3.3          4.85         5.56         6.7          7.0172
   8.7        9.32         10.6894      11.25        12.5         13.
   14.4       15.0         16.3         17.42        18.25        18.8
   19.270     20.1         20.98        21.67        22.4         22.94
   23.7       24.4         24.7         25.27        26.16        26.92
   27.69      28.24        28.6         29.291
 2*                    0.0
   1.08       2.215        3.3          4.4          5.54         6.65
   7.44       9.07         9.65         11.07        11.84        12.2
   13.25      13.88        14.3         15.4         15.95        16.5
   17.22      17.6         18.29        19.2         19.89        21.41
   21.95      22.81        23.27        24.43        24.97        25.63
   26.04      26.62        27.1         27.81        28.6         29.291
 8$
20R       113R        2           5
17R       116R        2           5
15R       118R        2           5
13R       120R        2           5
11R       122R        2           5
 9R       115R        2           3 8R        2           5
 9R       114R        2 4R        3 4R        2 3R        5
 9R       113R        2 5R        3 4R        2           5 2R        6
 9R       112R        2 7R        3 2R        2 2R        5 2R        6
 9R       111R        2 8R        3 2R        2           5 3R        6
 9R       110R        2 9R        3           2 2R        5 3R        6
```

```
 9R          1 0R          2 9R          3             2             5 4R          6
             2 8R          1 0R          2 8R          3 2R          2             5
 4R          6
 2R          2 7R          1 8R          2 0R          3 3R          5 4R          6
 2R          2 7R          1 8R          2 0R          3             5 6R          6
 3R          2 6R          1 7R          2 9R          3 2R          2             5
 6R          6
 5R          2 4R          1 7R          2 8R          3             2 3R          5
 6R          6
 5R          2 4R          1 7R          2 7R          3 2R          2             5
 8R          6
 7R          2 2R          1 6R          2 6R          3 3R          2 2R          5
 8R          6
 7R          2 2R          1 6R          2 5R          3 4R          2             5
 9R          6
22R          2 3R          5 9R          6
22R          2             5 1R          6
20R          2 3R          5 1R          6
20R          2             5 3R          6
17R          2 4R          5 3R          6
17R          2             5 6R          6
 6R          4 9R          2 3R          5 6R          6
 6R          4 9R          2             5 8R          6
 6R          4 7R          2 3R          5 8R          6
 4R          4 7R          2 3R          5 0R          6
 4R          4 7R          2             5 2R          6
 3R          4 6R          2 3R          5 2R          6
 3R          4 6R          2             5 4R          6
 2R          4 5R          2 3R          5 4R          6
 3R          2 5R          5 6R          6
 4R          5 0R          6
```

37X BY 35Y GEOMETRY - MESH AND MATERIAL SPECIFICATIONS - POISON IN WITH EXPLICIT VOIDS BETWEEN DRUMS AND CORE

```
 4*                    0.0
   1.08        2.08          3.3         4.20        4.85        5.40
   6.20        6.7           7.7         8.7         9.7         10.6894
   11.0        11.3          11.6712     12.5        13.41       14.20
   14.4        15.60         16.3        17.6        18.25       19.20
   19.80       20.1          21.62       23.00       23.7        24.80
   25.50       26.50         27.20       27.80       28.20       28.6
   29.291
 2*                    0.0
   1.08        2.215         3.3         3.45        4.4         4.80
   5.54        5.89          6.4         7.20        7.5         8.80
   9.50        10.51         12.2        13.25       13.8        14.3
   14.6        15.4          15.7        16.5        17.6        18.812
   19.1844     21.70         22.40       23.60       24.758      25.90
   25.90       27.60         28.20       28.6        29.291
 8$
26R          10R           2             5
23R          13R           2             5
21R          15R           2             5
```

```
19R      1 3R     714R     2        5
19R      1        7 5R     311R     2        5
16R      1 3R     7 5R     312R     2        5
16R      1        7 7R     312R     2        5
12R      1 3R     7        2        7 7R     312R     2
         5
12R      1 3R     2        7 7R     311R     2 3R     5
12R      1 3R     2 8R     311R     2        5 2R     6
12R      1 2R     2        7 7R     312R     2        5
 2R      6
12R      1        2        7 8R     312R     2        5
 2R      6
12R      1        7 8R     311R     2 3R     5 2R     6
12R      1        7 8R     311R     2        5 4R     6
12R      1        7 7R     312R     2        5 4R     6
         211R     1 2R     7 5R     313R     2        5
 4R      6
 2R      2        7 9R     1 3R     2 3R     312R     2
 3R      5 4R     6
 2R      4        7 9R     1 3R     2 3R     312R     2
         5 6R     6
 3R      4 2R     7 7R     1 4R     2        313R     2
         5 6R     6
 4R      4        7 7R     1 4R     2        313R     2
         5 6R     6
 5R      4 3R     7 4R     118R     2        5 6R     6
 6R      4        7        2 4R     116R     2 3R     5
 6R      6
 7R      4 3R     2 2R     116R     2        5 8R     6
 8R      420R     2        5 8R     6
 8R      417R     2 4R     5 8R     6
25R      2        511R     6
22R      2 4R     511R     6
22R      2        514R     6
17R      2 6R     514R     6
17R      2        519R     6
13R      2 5R     519R     6
13R      2 2R     522R     6
 7R      2 8R     522R     6
 7R      2        529R     6
 8R      529R     6
```

44X BY 45Y GEOMETRY - MESH AND MATERIAL SPECIFICATIONS - POISON OUT WITH EXPLICIT VOIDS BETWEEN DRUMS AND CORE

```
4*                0.0
  1.08     2.07     3.3      4.2      4.85     5.4
  5.56     6.2      6.7      7.0172   8.7      9.32
 10.5894   11.      11.25    11.3     11.6712  12.5
 13.       13.41    14.4     15.      15.6     16.3
 17.42     17.6     18.25    18.8     19.27    20.1
 20.98     21.67    22.4     22.94    23.7     24.4
 24.7      25.27    26.16    26.92    27.69    28.24
 28.6      29.291
```

```
2*                    0.0
   1.08        2.215        3.3         3.45        4.4         4.8
   5.54        5.89         6.4         6.65        7.2         7.44
   7.5         8.8          9.07        9.65        11.07       11.84
   12.2        13.25        13.88       14.3        14.6        15.4
   15.7        15.95        16.5        17.22       17.6        18.29
   19.2        19.89        21.41       21.95       22.81       23.27
   24.43       24.97        25.63       26.04       26.62       27.1
   27.81       28.6         29.291
 8$
30R         113R         2           5
27R         116R         2           5
24R         119R         2           5
21R         1 5R         717R        2           5
21R         1 2R         720R        2           5
18R         1 3R         722R        2           5
18R         1 2R         723R        2           5
13R         1 4R         7           2 2R        714R        2           3
 8R         2            5
13R         1 4R         2           716R        2           3 8R        2
            5
13R         121R         2           3 8R        2           5
13R         120R         2 4R        3 4R        2 3R        5
13R         1 2R         2 2R        716R        2 4R        3 4R        2
 3R         5
13R         1 2R         2 2R        715R        2 5R        3 4R        2
            5 2R         6
13R         1            2           717R        2 5R        3 4R        2
            5 2R         6
13R         1            718R        2 5R        3 4R        2           5
 2R         6
13R         1            717R        2 7R        3 2R        2 2R        5
 2R         6
13R         1            716R        2 8R        3 2R        2           5
 3R         6
13R         1            715R        2 9R        3           2 2R        5
 3R         6
13R         1            715R        2 9R        3           2           5
 4R         6
            212R         1 3R        713R        2 8R        3 2R        2
            5 4R         6
 2R         2            710R        114R        210R        3 3R        5
 4R         6
 2R         2            710R        114R        210R        3           5
 6R         6
 3R         2 2R         7 8R        112R        210R        3 2R        2
            5 6R         6
 4R         2            7 8R        112R        210R        3 2R        2
            5 6R         6
 5R         2 4R         7 4R        112R        2 9R        3           2
 3R         5 6R         6
 6R         2 2R         7           2 4R        112R        2 9R        3
            2 3R         5 6R        6
 6R         2 2R         7           2 4R        112R        2 8R        3
 2R         2            5 8R        6
11R         2 2R         111R        2 7R        3 3R        2 2R        5
 8R         6
11R         2 2R         111R        2 6R        3 4R        2           5
 9R         6
```

32R 2 3R 5 9R 6
32R 2 511R 6
30R 2 3R 511R 6
30R 2 513R 6
27R 2 4R 513R 6
27R 2 516R 6
10R 414R 2 4R 516R 6
10R 414R 2 519R 6
10R 411R 2 4R 519R 6
7R 411R 2 4R 522R 6
7R 411R 2 525R 6
5R 4 8R 2 6R 525R 6
5R 4 8R 2 2R 529R 6
3R 4 8R 2 4R 529R 6
5R 2 7R 532R 6
7R 537R 6

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TABLE I. - ENERGY-GROUP STRUCTURE

Lower energy bound[a]	Number of groups		
	26	13	4
	Cross-section set		
6.065 MeV	1	--	--
3.678 MeV	2	1	--
2.725 MeV	3	--	--
2.231 MeV	4	2	--
1.827 MeV	5	--	--
1.353 MeV	6	3	--
1.003 MeV	7	--	--
.821 MeV	8	4	1
.608 MeV	9	--	--
.498 MeV	10	5	--
.369 MeV	11	--	--
.302 MeV	12	--	--
.247 MeV	13	--	--
.183 MeV	14	6	2
.150 MeV	15	--	--
.111 MeV	16	7	--
67.4 keV	17	--	--
40.9 keV	18	8	3
24.8 keV	19	--	--
15.0 keV	20	9	--
9.1 keV	21	--	--
5.5 keV	22	10	--
2.0 keV	23	--	--
748.0 eV	24	11	--
78.9 eV	25	12	--
.414 eV	26	13	4

[a]Upper energy boundary is 14.9 MeV.

TABLE II. - ENDF/B CROSS SECTIONS USED IN GAM-II PROGRAM

Material	Isotope
1006	Lithium-7
1009	Boron-10
1140	Carbon-12
1013	Oxygen-16
1015	Aluminum
1111	Molybdenum
1126	Tantalum-181
1044	Uranium-235
1103	Uranium-238
1122	Iron

TABLE III. - MATERIAL SPECIFICATIONS BY REGION FOR RZ MODEL

Region	Density,[a] g/cm^3	Region									
		I	II	III	IV	V	VI	VII	VIII	IX	X
		Volume, percent									
[b]KelF	1.0	0.467	0.133	----	-----	-----	-----	-----	----	----	-----
B_4C	2.44	------	------	----	25.7	-----	-----	-----	----	----	-----
Al	2.7	------	4.63	----	3.62	-----	-----	4.63	42.0	23.0	4.74
Mo	10.2	------	54.9	90.8	54.3	-----	74.9	76.4	----	----	54.3
Ta	16.6	7.49	2.14	----	-----	100.0	7.49	2.14	3.9	----	-----
[c]U	18.9	26.3	7.53	----	-----	-----	-----	-----	----	----	-----
[d]Neoprene	1.23	------	------	----	-----	-----	-----	-----	23.7	----	-----
[e]Epoxy	3.7	------	------	----	-----	-----	-----	-----	1.6	----	-----
[f]$^7Li_3N$	.79	32.4	9.27	----	-----	-----	-----	-----	----	----	-----
304 Stainless steel	7.9	------	------	----	-----	-----	-----	-----	----	77.0	-----

[a]Use of these density values with the volume percents listed to calculate atom densities will reproduce those used in the calculations; the density and volume percents are not absolute.

[b]Coating on fuel rods; important constituent is 1.11-wt. % H.

[c]93.145-wt. % ^{235}U, remainder assumed to be ^{238}U.

[d]C_4H_5Cl.

[e]$C_{25}H_{34}O_7S_2$.

[f]95.62-wt. % $^7Li_3N$, 1.82-wt. % $^7Li_2$, 2.56-wt. % ^7LiOH.

TABLE IV. - EFFECT OF INPUT SPECIFICATIONS ON MULTIPLICATION FACTOR

[Gam cross sections.]

S_nP_l	Number of groups	Geometry	
		RZ	XY
		Multiplication factor	
S_4P_0	4	1.041	1.036
S_4P_1	4	1.039	1.036
S_8P_1	4	1.036	1.036
S_4P_1	13	1.030	1.023
S_4P_1	26	1.029	1.023
Experiment		1.011	

TABLE V. - 26-GROUP BORON-10

ABSORPTION CROSS SECTIONS

[Averaged over molybdenum reflector spectrum.]

Group	Cross-section set		Lower energy bound[a]
	GAM	GAM(ENDF/B 1009)	
	Cross section, barn		
1	0.0822	0.3177	6.065 MeV
2	.1449	.3914	3.678 MeV
3	.1781	.3431	2.725 MeV
4	.2220	.3730	2.231 MeV
5	.3475	.5138	1.827 MeV
6	.2853	.4112	1.353 MeV
7	.1967	.3005	1.003 MeV
8	.2410	.3421	.821 MeV
9	.3774	.4882	.608 MeV
10	.5669	.7144	.498 MeV
11	.6476	.8523	.369 MeV
12	.7991	.9376	.302 MeV
13	.9014	1.211	.247 MeV
14	1.101	1.454	.183 MeV
15	1.358	1.622	.150 MeV
16	1.670	1.795	.111 MeV
17	2.209	2.121	67.4 keV
18	2.908	2.660	40.9 keV
19	3.608	3.392	24.8 keV
20	4.543	4.399	15.0 keV
21	5.819	5.559	9.1 keV
22	7.458	7.127	5.5 keV
23	9.872	9.668	2.0 keV
24	15.84	15.87	748.0 eV
25	25.21	25.24	78.9 eV
26	75.00	75.07	.414 eV

[a]Upper energy boundary is 14.9 MeV.

TABLE VI. - CALCULATED REACTIVITY WORTH

OF CONTROL DRUMS

Case	Calculation	Cross section	Reactivity worth, $
1	S_4P_0 4-group	GAM	9.59
2	S_4P_1 4-group	GAM	9.69
3	S_4P_1 13-group	GAM	9.56
4	S_4P_1 13-group	GAM(ENDF)	10.72
5	S_4P_1 13-group	GAM except GAM(ENDF) ^{10}B	10.45
6	S_4P_1 13-group with explicit VOID[a]	GAM(ENDF)	11.61
7	S_4P_1 26-group	GAM except GAM(ENDF) ^{10}B	10.54
Experiment (inverse kinetics)[b]			11.58

[a]XY geometries 3 and 4 (appendix) used for this case; all other cases use geometries 1 and 2 to obtain control swing.

[b]Inverse counting method gave $11.98.

TABLE VII. - ATOM DENSITIES FOR XY CALCULATIONS

[Region numbers correspond to those in geometry specifications.]

Isotope or element	Region[a]			
	1 (Fuel cells)	2 (Reflector)	3 and 4 (Boron carbide)	5 (Pressure vessel)
	Atom density, atoms/barn-cm			
H	0.0001947	----------	---------	--------
^7Li	.0129834	----------	---------	--------
O	.0002579	----------	---------	--------
N	.0042108	----------	---------	--------
Al	---------	[b]0.0024123	---------	--------
Mo	---------	[b].0541190	---------	--------
Ta	.0041422	----------	---------	0.044116
B	---------	----------	0.0739140	--------
C	---------	----------	.0184876	--------
^{235}U	.0118576	----------	---------	--------
^{238}U	.0008727	----------	---------	--------

[a]A sixth region located outside the pressure vessel is void and zero cross sections were used.

[b]For the two cases which had an explicit void between core and control drums (designated region 7), the reflector atom densities were adjusted accordingly to 0.055586 for Mo and to 0.0024753 for Al. The transverse leakage from region 7 is based on use of the transport cross section of region 2.

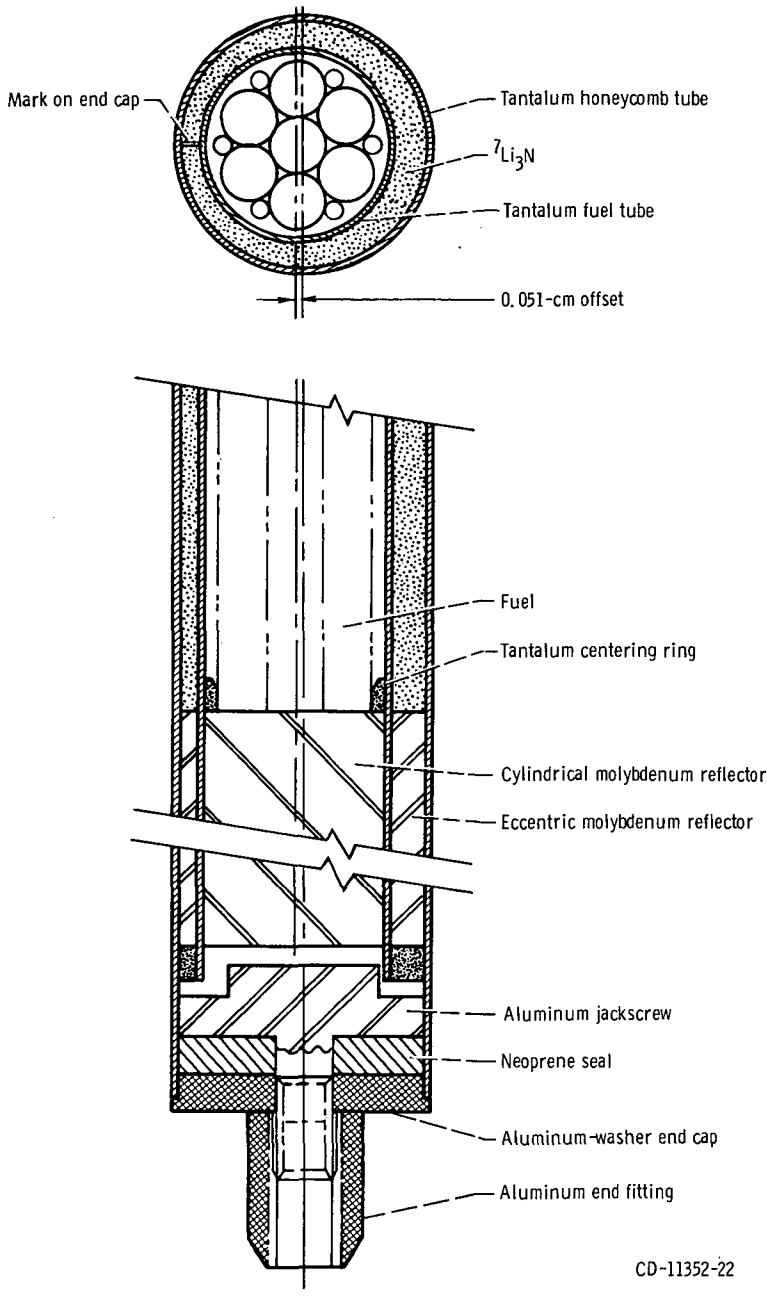


Figure 1. - Fuel element for critical experiments. Outside diameter, 2.16 centimeters.

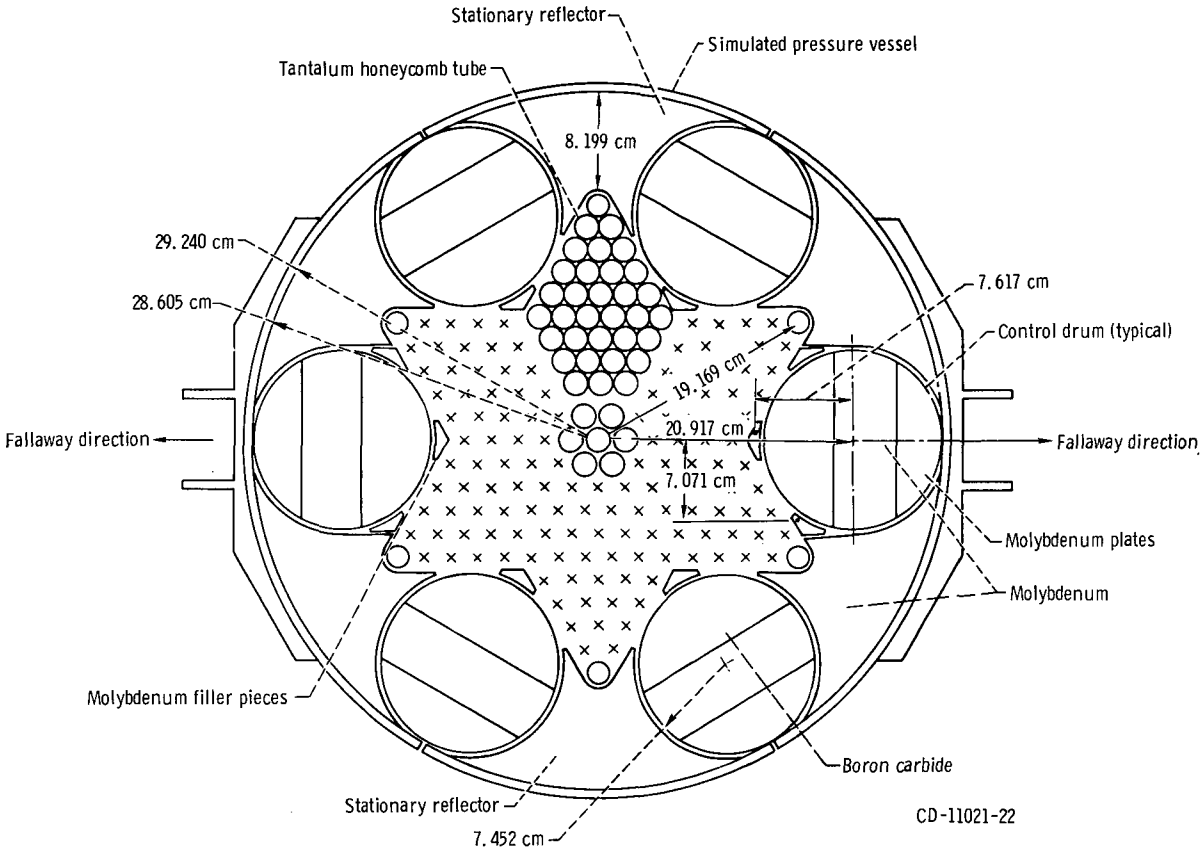
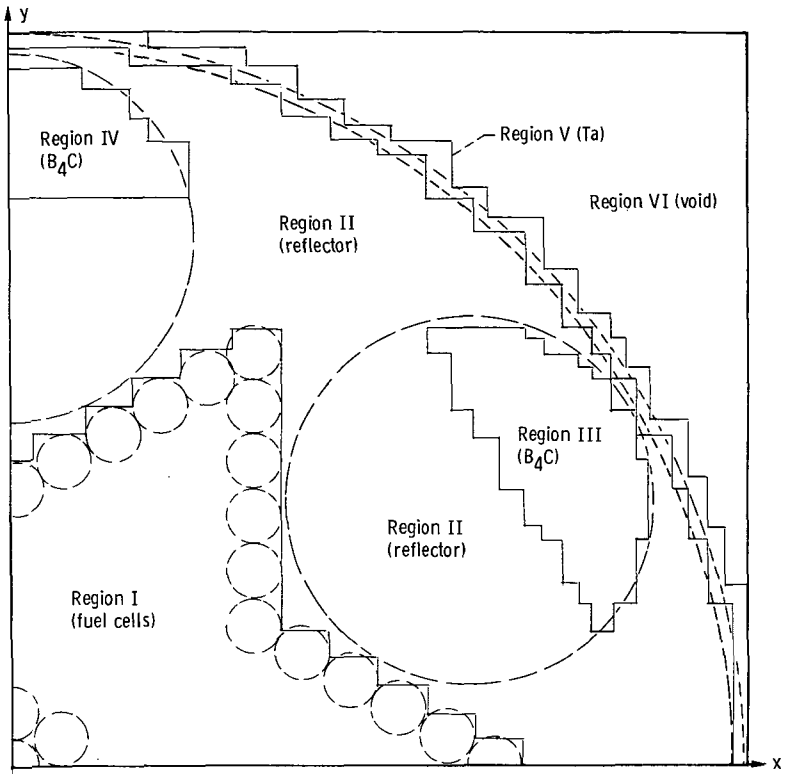
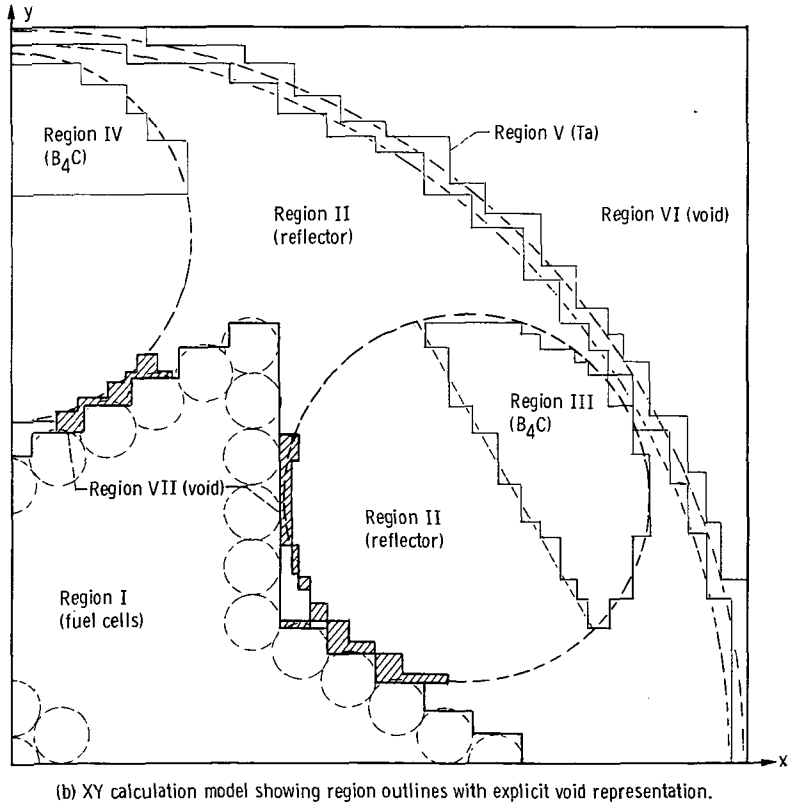


Figure 2. - Cross section of critical assembly.



(a) XY calculation model showing region outlines.



(b) XY calculation model showing region outlines with explicit void representation.

Figure 3. - XY calculation model. Control drums in poison out position.

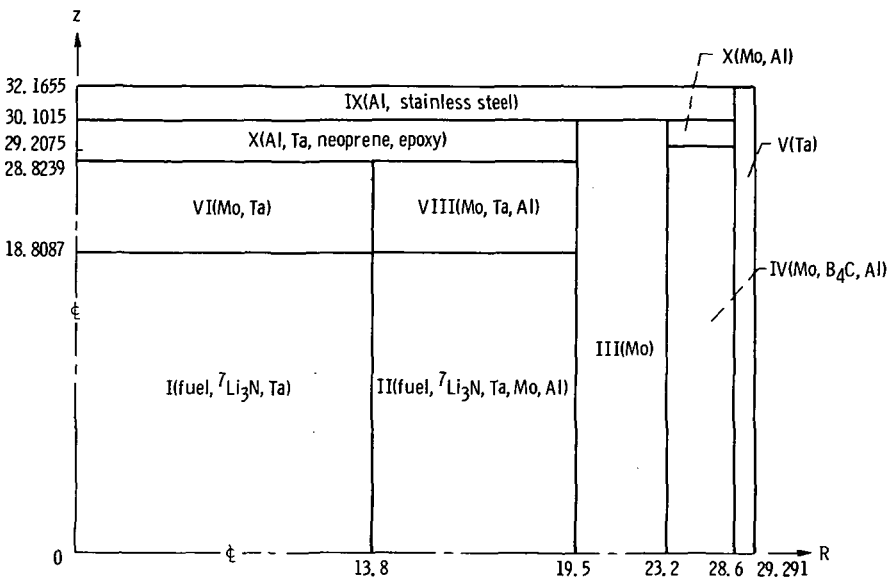


Figure 4. - RZ calculation model (not to scale). Dimensions are in centimeters. Roman numerals designate regions specified in table III. Control drums in *poison-out position.*

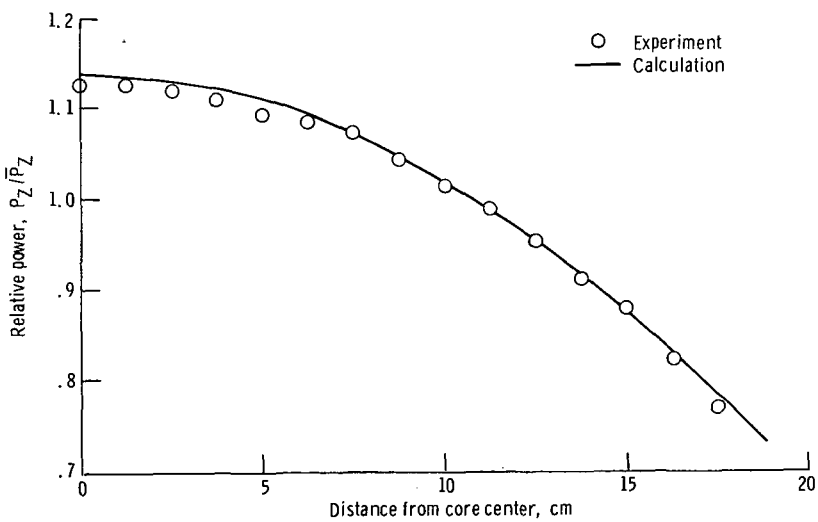


Figure 5. - Axial power distribution in boron-carbide-controlled reactor.

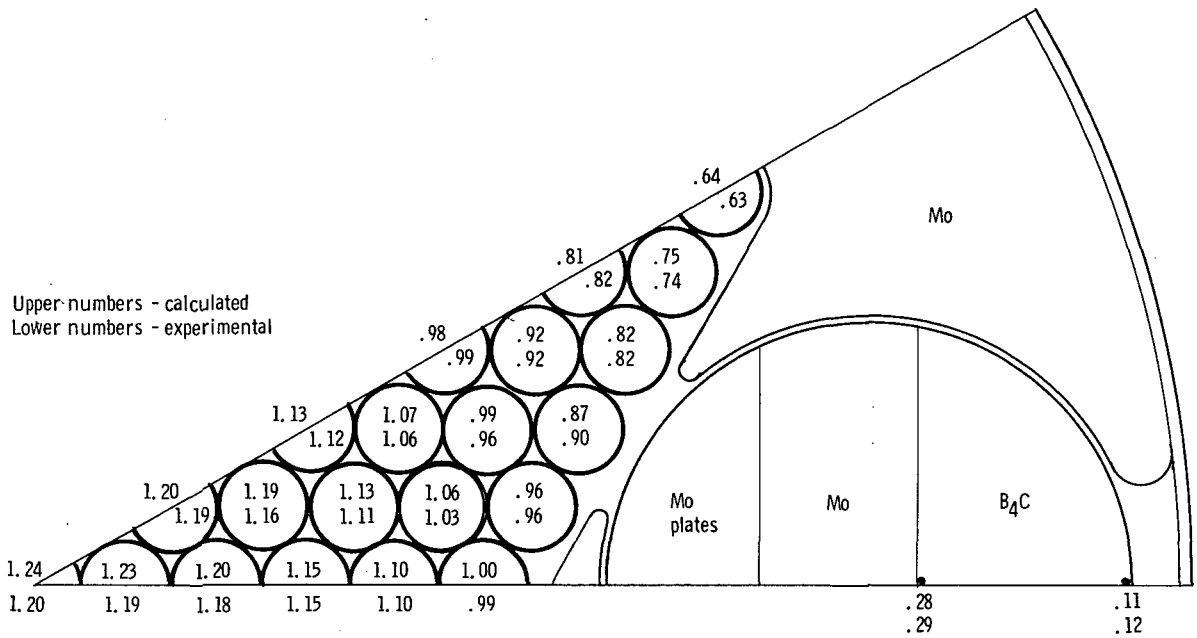


Figure 6. - Relative power distribution in boron-carbide-controlled reactor - S_4P_1 13-group XY calculation. Multiplication factors: $k_{exp} = 1.011$; $k_{calc} = 1.018$.

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